



Hendry, K. R., Meredith, M. P., & Ducklow, H. W. (2018). The marine system of the West Antarctic Peninsula: status and strategy for progress. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2122), [20170179]. <https://doi.org/10.1098/rsta.2017.0179>

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[10.1098/rsta.2017.0179](https://doi.org/10.1098/rsta.2017.0179)

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The marine system of the West Antarctic Peninsula: status and strategy for progress

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Keywords: Insert a minimum of three and maximum of six keywords here.

Main Text

The West Antarctic Peninsula (WAP; Figure 1) is one of the most climatically sensitive regions on Earth, and one of the most climatically variable. The strong climatic variability gives us the opportunity to study and understand how the ocean responds to - and feeds back on - climate change, hence learn about the key mechanisms that are at work, which might apply around the Southern Ocean as a whole. Data coverage is still inadequate across the Southern Ocean (because of remoteness and harsh conditions) and, despite being better observed than many other regions around Antarctica, the nature of oceanographic and atmospheric change on the WAP is poorly constrained. This special issue addresses some of the most important and pressing questions surrounding marine system variability at the WAP: how has the WAP changed, and how will it change in future? What's driving these changes? And why is there such an extraordinary degree of spatial and temporal variability in the region?

These questions were addressed in two interlinked meetings held in 2017. A two-day meeting was hosted in May at the British Antarctic Survey (BAS) in Cambridge, UK (co-sponsored by the Southern Ocean Observing System, the Scientific Committee for Antarctic Research and the Scientific Committee for Ocean Research), aimed at gathering and critically assessing a broad view from the international community on the gaps and challenges in WAP oceanographic research. A second meeting was held at the Kavli International

Centre at Chicheley Hall (funded by the Royal Society) specifically to identify the key outstanding biogeochemical questions relevant to the WAP, and how they could be addressed through tangible means, including through the integration of physical and biological studies. This special issue features contributions from attendees of these two associated meetings, focusing on the physical and biological interactions that impact biogeochemical cycling along the WAP, with a view to elucidating the state of the art of the science and elucidating the overarching issues on which future research effort should be prioritised.

Broadly speaking, physical climate dynamics drive the significant spatial and temporal heterogeneity at the WAP via mechanisms including exchange processes between open ocean and shelf waters (reviewed by Moffat et al., this issue [1]), sea-ice variability, atmospheric interactions and glacial inputs. However, there are important gaps in our understanding of the nature of the links between physical forcing and biogeochemical cycles, and the resulting feedbacks on the climate system that act primarily through biotic response. We need high-resolution, sustained observational datasets that cover a wide geographical range of the WAP, together with sophisticated approaches to modelling, to address these gaps. Long time series are critical within this, such as the year-round Rothera Time Series (RaTS) programme that operates from the BAS Research Station on Adelaide Island. Another example of a valuable long-term dataset is the Palmer Long Term Ecological Research (PAL-LTER) program, which includes time-series sampling at the US Palmer Station (Anvers Island), and decades of data from annual expeditions that occupy a grid of stations along the WAP [2]. Schofield et al. (this issue [3]) present 24 years of PAL-LTER data to assess changes in primary production and physical forcing, including sea-ice extent and mixed layer depth. Their analysis reveals strong regional differences and a north-south gradient in phytoplankton response, which provides information about possible driving mechanisms for change and key insight into future change. Whilst bringing together this unprecedented dataset, our understanding would be improved even further if it was possible to include data from throughout the year, in addition to summer snapshots.

Primary production along the WAP is strongly linked with sea-ice duration, extent and timing of spring melt, and the impact of these factors on water column stability and light availability [3-5] and inputs of key macronutrients and trace elements from a variety of sources, linked with glacial meltwater and sediment interactions (Bown et al., this issue [6]; Henley et al., this issue [7]; Sherrell et al., this issue [8]). 'Productivity hotspots' of high phytoplankton standing stocks, such as Palmer Deep and Marguerite Bay, provide an example of extreme heterogeneity in WAP primary production. The previously existing paradigm to explain the

existence of 'hotspots' is based on the premise that the productivity is controlled by 'bottom-up' processes, whereby nutrients feed phytoplankton such as diatoms, which feed krill and higher trophic levels. Patchy productivity arises as a result of patchy nutrient supply, fed into surface waters from intrusions of Circumpolar Deep Water (CDW) onto the shelf, funnelled by canyons that were calved by glaciers during the last ice age [9]. However, new contributions in this special issue highlight challenges to this paradigm. Kohut et al. (this issue) [10] use High Frequency Radar to show that the residence time of phytoplankton is much shorter than their growth rate, implying that phytoplankton are concentrated in 'hotspots' by physical transportation rather than by growing *in situ*, and canyons are "conveyor belts" rather than "incubators". There is increasing evidence that shelf sediments may be a more important source of macronutrients and trace elements rather than deep water [6,8], in addition to water column modification due to organic matter remineralisation [7]. New geochemical analyses from Sherrell et al. (this issue) show that there is considerable supply of key trace elements, such as iron, by horizontal advection of particulate and dissolved species from shallow-sediments (constituting a "bathtub ring") providing localised rather than regional supplies from water masses [8]. Contrasting ratios of metals in different regions suggest that these sources may differ between the 'hotspots', with no one mechanism to explain nutrient enrichment along the length of the WAP.

The Southern Ocean is also the region of highest variability in climate-active gases such as dimethylsulphide (DMS) and its precursor dimethylsulphoniopropionate (DMSP), with high concentrations in the marginal ice zones, and significant variability within and between seasons. As for primary production, DMSP to DMS conversion depends on interrelated physical and biological processes, such as stratification, nutrient availability, light penetration, and plankton community structure. The upshot of strong links between sea-ice production and DMS(P) production along the WAP is that there is likely an important climate feedback that will be increasingly active in the future (Stefels et al., this issue [11]).

Higher trophic levels and benthic consumers are supported by primary production, which underpins the entire ecosystem [12], in addition to being a key sink of atmospheric carbon dioxide [13]. The benthos is also an important carbon sink, representing considerable standing stocks of organic matter. As for the plankton and nekton, the WAP benthic community is also impacted by direct physical processes - such as iceberg scouring and glacial meltwater releases - that are likely to change into the future with consequences for diversity and carbon storage (Barnes et al., this issue [14]; Jerosch et al., this issue [15]). Physical processes

Phil. Trans. R. Soc. A.

also impact the benthos indirectly via the sinking of organic matter that originates in the photic zone (export production), which result in complex and highly variable pelagic-benthic coupling. Quantifying export production directly through capturing sinking particles has been challenging, due to differing efficiencies of sediment traps and poor spatial resolution (reviewed in [16]). Different geochemical methods can be employed to quantify export production (e.g. radioisotope measurements, [16]; triple oxygen isotope measurements, [17]), but these methods can yield conflicting results due to averaging over different timescales, and because of assumptions about the duration of the growing season. Ducklow et al. (this issue [18]) compile three years' worth of geochemical data collected from the PAL-LTER grid and calculate new production and net community production along the WAP, which they show can be considerably greater than sinking particle export. Their findings highlight that other processes in addition to sinking are important in determining export such as lateral advection and vertical mixing, adding further complexity to quantifications and full understanding of pelagic-benthic coupling.

There is considerable work underway to identify and quantify the key processes that link physical climate forcing, biogeochemistry and marine ecosystems, and the respective rates and spatial scales. A number of new analytical and theoretical tools have become available. Geochemical methodologies, especially those employing high-resolution isotopic variations, can provide considerable insight into the nature of these processes. Meredith et al. (this issue [19]) use a novel high-resolution approach to existing isotopic methods to characterise and trace episodic meltwater release off King George Island (Isla 25 Mayo), northern WAP, and elucidate the structure of a specific glacial discharge event in unprecedented detail. Strong dependence on atmospheric variability is found, with influences from both air temperature (via the amount of glacial melt discharge) and winds (which impact the retention and fate of freshwater in the ocean). This points to potentially strong future climatic changes in such discharge events. Several glaciers on King George Island are, in recent years, becoming land-terminating, and may be useful predictors of future change further south along the peninsula as glacial retreats there continue [20]. Adopting an alternative approach to a similar problem, Falk et al. (this issue [21]) employ statistical methods capable of dealing with sparse datasets, namely Monte Carlo and Fourier analysis, to estimate hydrological discharge off King George Island. Similar to Meredith et al (this issue), they also highlighted the strong dependence on atmospherically-driven circulation and surface air temperature [19].

Long-term solutions to addressing WAP oceanographic variability across different disciplines will require continued long-term monitoring from all engaged nations, in addition to improved data availability and sharing. Bringing complementary datasets together from different international efforts is especially important if we are to deconvolve regional versus local signals in such a highly heterogeneous environment (Kim et al., this issue [22]). Drawing in other disciplines that will mesh with marine science such as glaciology, atmospheric science and palaeoclimate will also be critical. Engagement with other organisations and with policy, industry, education and with the public via 'citizen science', through dialogues with cruise ship operators, and development of apps and approachable literature.

The contributions to this special issue illuminate the state-of-the-art in our understanding of oceanographic variability, and the drivers and processes underlying this variability. However, there remain scientific concerns from across all WAP disciplines surrounding the challenges in understanding the complexities of the highly heterogeneous WAP marine system at different spatial and temporal scales, coupled with heavy sampling bias and logistical limitations. There are further strategic developments that are either touched upon or not covered in this special issue, in technological advances, sampling methodologies, and networking of platforms, research infrastructure, and people within and between disciplines. There is an urgent need for greater resolution of sampling throughout the Antarctic year, with effort needed to fill gaps in key winter and early spring seasons. High Frequency Radar networks, gliders and other autonomous underwater vehicles will, eventually, be able to operate throughout the year. There are also fast evolving developments in model capability and data-model integration [1]. A greater understanding will also come with a more holistic approach to addressing spatial and temporal variability, building links between empirical research and modelling, and between physical, chemical and biological disciplines.

Funding

KH is a University Research Fellow of the Royal Society, and is funded by a European Research Council Starting Grant.

Acknowledgments

The authors would like to thank the Royal Society, British Antarctic Survey, Southern Ocean Observing System, Scientific Committee for Oceanographic Research and Scientific Committee for Antarctic Research for supporting the scientific meetings, from which this special issue arose. Many thanks to all participants of the

meetings, and to Sian Henley, Louise Newman, Oscar Schofield, Grace Mooring and Tracey Sharpe for their help in organising the events.

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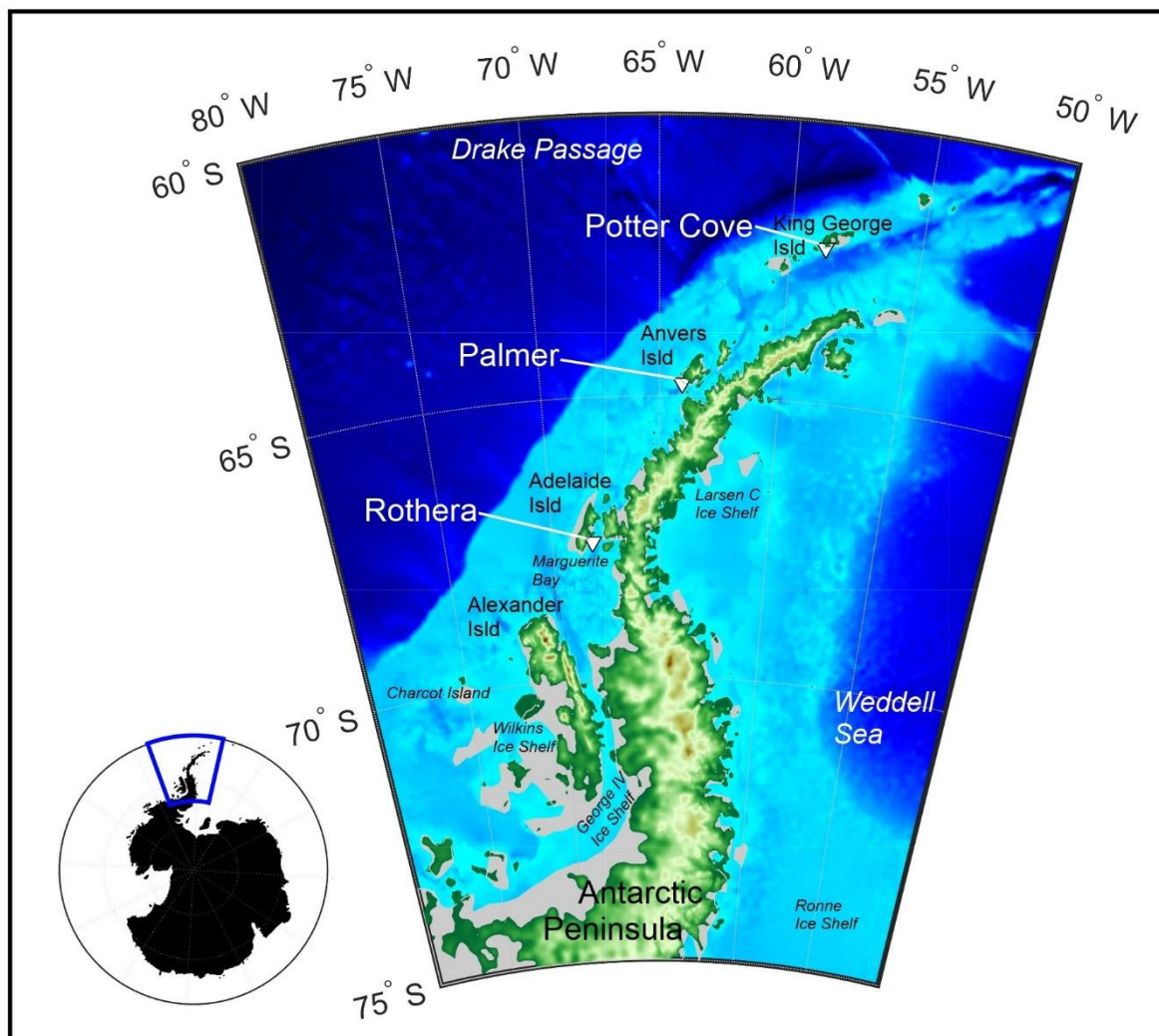


Figure caption

A map of the Antarctic Peninsula, showing main islands and ice shelves, with key research locations marked with triangles. Main map is enlarged view of blue box, and was made using etopo1 bathymetry.